THE STRENGTH OF THE EARTH'S CRUST—*Concluded*

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PART VIII. PHYSICAL CONDITIONS CONTROLLING THE NATURE OF LITHOSPHERE AND ASTHENOSPHERE

SECTION B

RELATIONS WITH OTHER FIELDS OF GEOPHYSICS

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Erroneous Conclusions Reached by the Rectilinear Projection of Surface Conditions

Geologists early became aware that temperature increased with depth. Projecting this gradient as a straight line indicated that at no great depth the temperature was sufficiently high to melt all rocks and, in testimony, volcanoes brought such melted rocks to the surface. The earth was consequently looked upon as a molten or even gaseous body enveloped by a thin crust of solid rock. The logic of this conclusion seemed incontrovertible and moreover it was in accord with the simpler expectations from the nebular hypothesis. Nevertheless, direct and positive evidence from several independent sources has forced on geologists the belief that the earth is not only solid throughout, but, as a whole, is more rigid than steel. Slowly and with difficulty the older view has therefore had to be abandoned. Yet it continually recurs in one form or another, advocated chiefly by writers who see the direction in which the surface evidence of temperature gradient leads, who regard it as compulsory, and who do not recognize or give equal

weight to the direct evidence regarding the nature of the earth's interior. Because of the ease and certainty of laboratory studies there is a tendency to treat the interior of the earth as though it were incapable of speaking for itself through the evidence of geophysics, geodesy, and geology, but must remain forever a playground for the speculative imagination. Largely unknown the nature of the earth's interior is and long must be; laboratory studies on the influences of heat, of pressure, and of chemical composition, upon the physical state of the crust, must constitute the paths which guide in the search downward into the unknown; but the final test of hypothesis must be the direct testimony of the earth itself.

The rectilinear projection of surface conditions is based on the assumption that the temperature gradient is a straight line to great depths, or that strength, or density, or porosity, as the case may be, is not changed by the pressures of the interior. Such assumptions lead to views more or less in opposition to those reached in the present investigation. They must, therefore, be discussed to some degree. An illustration of these dangers of reasoning by unchecked extrapolation is supplied by a paper written by Arrhenius,[1] selected for discussion because of the eminence of the author in the fields of physics and chemistry, the definiteness with which his conclusions are stated, and the wide citation which this paper has achieved.[2] In this paper the arguments are given in favor of a gaseous nature of the interior of the earth, carrying forward an idea first suggested by A. Ritter in a series of "Researches on the Height of the Atmosphere and the Constitution of Gaseous Heavenly Bodies."

From the rate of increase of temperature with depth Arrhenius argues that at a depth of 40 km. the crust must pass into a molten condition, but one which, because of pressure, is a viscous and highly incompressible liquid. At a depth of some 300 km. the temperature, he states, must be above the critical temperature of

[1] "Zur Physik des Vulkanismus," *Geol. Foren. i Stockholm, Forhandl.*, XXII (1900), 395–419.

[2] See for example its presentation by A. Geikie, *Text Book of Geology*, Vol. I (1903), pp. 71–74.

all known substances, and therefore the liquid magma passes into a gaseous magma extending to the center of the earth. The author then notes that the chemical elements of highest atomic weight are not detected in the sun, but states that without doubt they occur, and concludes from this that they must be concentrated by virtue of gravity toward the sun's center.[1] The high density of the earth's interior is accordingly to be explained by the presence of substances heavier than surface rocks. For many reasons, as the dominance of iron in nature, as shown by meteorites, by the spectrum of the sun, and by the magnetism of the earth, it is to be concluded that this substance which he thinks necessary to account for the high density of the earth's interior is metallic iron. The earth consists consequently of the following portions measured from the center on the radius. Eighty per cent of the radius is gaseous iron, 15 per cent is gaseous rock magma, about 4 per cent is fluid rock magma, and somewhat less than one per cent is solid crust.[2]

To reconcile these conclusions with the incontrovertible evidence of rigidity, Arrhenius takes up another line of rectilinear extrapolation and carries it to an equally extreme degree. Fluids in general show a somewhat readier compressibility than solids. At high pressures then it is argued that liquids will customarily occupy less volume than solids and the pressure will tend to lower, not raise, the melting-point. Consequently, the rigidity cannot be accounted for by the maintenance of solidity through pressure. The author then points out that under enormous pressures all substances, even gases, must become highly incompressible; and that at high temperatures, where the volume is maintained the same, the viscosity of gases or fluids increases with increase in temperature. From this it is argued that in the central parts of the earth gaseous iron is more incompressible and viscous than solid steel. It is by enormous pressure consequently in spite of a gaseous nature that the interior of the earth exhibits its great rigidity.

Vulcanism according to Arrhenius is connected with the free seepage of ocean water downward through the crust which, he holds, constitutes a semipermeable membrane. By the absorp-

[1] *Op. cit.*, p. 402. [2] *Op. cit.*, p. 405.

tion of water into the heated rocks the conditions for volcanic activity are initiated. This argument, like the others, is in the form of a great extension or extrapolation of factors operative in a small way in the laboratory to conditions in nature which are wholly different in magnitude.

As comments upon this paper, it should be noted that nearly every conclusion applying to the sun and earth may be questioned.

At a depth of 1,000 km., according to Arrhenius, the temperature is about 30,000° C. The gradient is thus taken as essentially a straight line from the surface downward. There is no demonstration as to why this rectilinear extension is assumed, whether it is to be regarded as an adiabatic temperature curve produced by condensation under pressure or produced in some other way. The influence of cooling through geologic time in changing the outer gradient is not considered; nor the influence of rising magmas. The existence of radioactivity was then just beginning to be appreciated and naturally could not have been evaluated, but the data for a discussion of the other factors, though at hand, was neglected.

There is no demonstration that the heavy elements are concentrated in the sun's interior, or that the earth is mostly metallic iron. It is possible that the earth is thus constituted, but it must be proved on better evidence than a citation of the dominance of iron in nature. The incompressibility of all substances, both fluid and liquid, increases greatly with great increase of pressure following apparently parabolic curves. Therefore, it cannot be argued with any assurance that the high incompressibility of the earth's interior proves the presence of iron, or that under such pressures the fluid occupies less volume than the solid state.

At a depth of 1,000 km. Arrhenius states that the temperature is about 30,000° C. and the pressure 250,000 atmospheres.[1] If, under these conditions of exalted temperatures, gaseous rock or iron has a viscosity equal to that of solid steel it may well be asked how the stars, with their immensely greater masses and consequent internal pressures, can maintain a convective circulation competent to keep up their enormous surface radiation. Furthermore, however viscous a compressed gas or liquid may be, this property

[1] *Op. cit.*, p. 400.

should be distinguished from rigidity. If a body can resist even small shearing stresses for an indefinite period, it has the essential properties of a solid and not a gas. If it possesses real rigidity, even if it should be true that under relief from pressure the substance would turn into a gas, yet such relief cannot take place and it is a confusion of terms to speak of the substance as a gas when exhibiting to a striking degree the essential qualities of a solid. This distinction between viscosity and rigidity is of first importance, yet is not mentioned by Arrhenius. Although undercooling of a fluid into a glass gives rise to the elastic properties of a solid, it has not been shown that increase of pressure, however great, upon a gas above the critical temperature would transform increasing fluid viscosity into solid rigidity and plasticity such as is exhibited by the earth.

As to the hypothesis that the crust is a semipermeable membrane, permitting a free downward seepage of ocean water, but little need be said, since this is a subject which has been much discussed in recent years and is now largely discarded by geologists. The evidence against it is varied. Petrologic study shows the deep rocks to be impermeable and unaltered; beyond a shallow depth they are dry, and their gaseous and liquid occlusions are held unchanged for geologic ages. Unsound conclusions have been built upon the behavior of steam within porous sandstones, combined with confusion of the rate of diffusion under enormous pressure-gradients in the laboratory with enormous pressures, but low pressure-gradients within the crust. Furthermore volcanoes are not restricted to the vicinity of the sea and their emanations are not of the proper composition to have been derived from ocean waters. As Suess has said, volcanoes are not nourished by the sea, but every volcanic eruption adds to the waters of the ocean.

The paper under discussion was written by a scientist who has done much exact work in physical chemistry, but who in passing to geologic thinking has adopted the habit of an earlier generation —a habit of speculative thought, suggested by chemical and physical concepts and not verified by a study of the earth. The form of present geologic investigations has, however, advanced to the quantitative stage, although the data are often so inexact that the

order of magnitude, or the direction of the truth, is all which may be now ascertainable.

In conclusion, it is seen that the hypotheses outlined by Arrhenius imply a thinness of the crystalline lithosphere and a crustal weakness wholly at variance with the conclusions regarding strength which have been reached in this investigation. They imply a difference in nature of the earth's interior from that given by the more direct lines of evidence, as shown by the body resistance of the earth to vibratory distortions of both short and long periods. Because of these many difficulties, this group of hypotheses, adopted by Arrhenius, has already been largely discarded, though they still find considerable acceptance, more especially by workers in related fields of science. But the measures of lithospheric depth and strength which appear to be given by geodesy add their testimony to the cumulative evidence against these views.

THE EVIDENCE OF TIDES ON RIGIDITY AND STRENGTH

The tidal distortion of the solid earth measured by means of the horizontal pendulum has shown that its rigidity is of the order of magnitude of steel. But the recent measurements by Michelson and others, employing a long horizontal pipe partly filled with water, showed clearly that the earth's rigidity is even greater than that of steel.[1] This higher value is in agreement with the inductions from the observations on the variations of latitude. But these measurements give the rigidity of the earth as a whole, not the distribution of rigidity. The resistance to tidal deformation is furthermore complicated by the influence of gravity and increasing density with greater depth. Even if the earth were a liquid globe it would resist tidal distortion to one-third the degree of the resistance of a globe of steel, and if the liquid sphere were denser inside, this ratio would be further decreased.[2] Notwithstanding this factor, however, it is clear that the earth as a whole is more rigid than steel. As the outer part is known to be less rigid than steel, it follows that the rigidity of much of the interior must be

[1] "Preliminary Results of Measurements of the Rigidity of the Earth," *Jour. Geol.*, XXII (1914), 118.

[2] A. E. H. Love, *Elasticity*, p. 306.

proportionately higher. But the tidal stresses, though serving as a measure of the rigidity of the earth as a whole, are so small that they are ineffective as a measure of the strength of the earth as a whole, or of even its weakest parts. The smallness of the stresses can be appreciated by noting Darwin's numerical calculations. In his original paper Darwin arrived at the conclusion that the tidal stress-differences at the center of the earth were eight times as great as at the surface, and this result has been widely quoted. In the final publication, however, a correction is made showing that this is the ratio between the surface stress *at the poles* as compared to the center. The stresses at the poles, at the equator, and at the center he finds to be in the ratio of 1 to 3 to 8. The diurnal tide gives an actual stress-difference per square centimeter amounting to 16 grams at the poles, 48 at the equator, and 128 at the earth's center.[1] The strength of granite at the surface of the earth averages about 1,700,000–2,000,000 grams per square centimeter. The elastic limit for steel subjected to tensile or compressive stresses in one direction ranges from about 3,500,000 grams to 4,500,000 grams per square centimeter, according to the grade of the metal. The ultimate strength is about twice as high as the elastic limit. Thus the earth is stressed by the tidal forces even at the center to only about one part in fifteen thousand of the strength of good granite at the surface, or about one part in twenty-seven to thirty-five thousand of the limits of perfect elasticity which steel exhibits in the laboratory. With stresses so small it is not surprising that although tides give measurements of rigidity their evidence regarding viscosity is most uncertain. The results of estimates of the viscosity are more or less contradictory and so small as to be within the probable error of determination. Nevertheless Schweydar considers that there is a suggestion of a slightly plastic zone extending from a depth of about 120 to 620 km. Although this has been adopted in the present article as the limit of the asthenosphere, it would appear that the convincing proof for the existence of such a zone, and the determination of its limits

[1] George H. Darwin, "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains," *Collected Scientific Papers* (1908), II, p. 481; original publications, *Phil. Trans. Roy. Soc.*, CLXXIII (1882), 187–223, and *Proc. Roy. Soc.*, XXXVIII (1885), 322–28.

also is more likely to be given by the geologic and geodetic evidence rather than from that yielded by the tides, provided that the present hypothesis of the existence of an asthenosphere is accepted.

It might seem that if the asthenosphere is strained to its limit by permanent stress and is slowly yielding, that even the small and rhythmic tidal stresses, like the last straw on the camel's back, might reveal a lack of resilience in the region of yielding. The distinction was emphasized in Section A, however, that an elastic limit which is determined for permanent stress by a facility of recrystallization at a high temperature may be a far lower elastic limit than that which would exist for rapid rhythmic stresses. Recrystallization would theoretically go forward a little more rapidly during the additive phase of the tidal stress, but the process is presumably so slow, and the tidal stress so small and rapid, that no appreciable effects would be attained before the following of the negative phase. A high resilience of the earth under tidal stress seems therefore quite compatible with the existence of a slowly yielding asthenosphere.

THE EVIDENCE OF EARTHQUAKE WAVES ON RIGIDITY AND DENSITY

The speed of an elastic wave through a solid varies directly with the square root of the modulus of elasticity and inversely with the square root of the density. There are two waves, corresponding to the elasticities of volume and form respectively, the one measured by the modulus of compressibility, the other by the modulus of rigidity. The first is the longitudinal or radial wave, the second is the transverse wave. The former outruns the latter and gives rise to the first preliminary tremor by which the earthquake records itself in distant regions. The transverse vibration is felt as the second preliminary tremor, followed by the much larger oscillations of the principal wave. The first two go through the earth, the latter passes around the surface. The fact that there is a transverse wave shows that the earth is solid throughout. But the vibrations at the point of emergence for waves which have penetrated more than half-way into the earth are so faint because of distance that their beginnings are in doubt, and consequently the speeds of transmission below one-half of the radius are uncer-

tain. These greater depths do not, however, so immediately concern the present subject. For the outer quarter of the earth both radial and transverse waves increase in velocity of transmission with depth, showing that incompressibility and rigidity increase faster than density and reach values greater than those exhibited by steel at the surface of the earth.[1]

So much is certain, but when it comes to testing the character of any particular shell by means of the velocities and character of the vibrations which have passed through it, there is but little certainty. The difficulty of an exact interpretation is discussed well by Knott.[2] To illustrate the variety of opinions, Benndorf has worked out a law according to which the speed of transmission increases rapidly to a depth of 200 miles (320 km.) from the surface. Knott assumes a constancy of speed below a depth of 400 miles (644 km.).[3] Wiechert has concluded that there are sudden changes in velocity at depths of 1200, 1650, and 2450 km. Poisson's ratio which expresses the relationships of the elasticities of form and volume remains, however, practically constant throughout, having a mean value of 0.27.[4] These changes imply surfaces of discontinuity. If real, however, they are deeper than the shells of the earth involved in the problems of isostasy. The conclusions rest, however, upon data of doubtful reliability. Reid has made a critical examination of this subject in connection with his comprehensive study of the excellent records obtained from many parts of the world of the California earthquake of 1906.[5] Following Wiechert's method, the curves representing the normals to the wave fronts and the velocities at various depths were computed from the data of the seismograms. The result showed that for the radial or longitudinal wave the velocity increased rapidly with depth but with decreasing rapidity, from 7.2 km. per second at the

[1] Galitzen, *Vorlesungen über Seismometrie*, p. 138, 1914.

[2] *Physics of Earthquake Phenomena* (1908), chap. xii.

[3] *Op. cit.*, pp. 248–50.

[4] G. W. Walker, *Modern Seismology*, 1913, p. 61.

[5] *California Earthquake of April 18, 1906* (Report of the State Earthquake Investigation Commission, Vol. II, "The Mechanics of the Earthquake," by H. F. Reid). Published by the Carnegie Institution of Washington, 1910.

surface to 12.5 km. per second at 2,170 km. from the surface, 0.66 of the radius from the center. Below that depth the velocity is nearly constant. The velocity of the transverse waves is 4.8 km. per second at the surface and increases almost linearly with depth, reaching a velocity of about 7.5 km. per second at half the distance to the center of the earth. The absence of good records from distances beyond 125° prevents a knowledge of the velocities at greater depths. Within the limits regarding which information is given, Reid remarks that there is no indication of a sudden change in the velocity of either wave such as we should expect if there were any sudden changes in the nature of the earth's interior. Oldham also finds no evidence of sudden change to a depth of at least 2,400 miles, 0.4 radius from the center.[1] From the curves showing the relation of velocity to depth which Reid gives[2] it is seen that the ratio of velocity of the transverse to the velocity of the longitudinal wave is 0.66 at the surface, 0.56 at 0.95 R, 0.53 at 0.9 R, reaching a minimum of 0.52 at 0.85 R, from which it increases to 0.58 at 0.5 R. This shows that both moduli of elasticity increase with depth, but that down to a depth of between 0.8 and 0.9 R. from the center of the earth, 637 and 1,274 km. from the surface, incompressibility increases relatively faster than rigidity. The change is shown as very rapid in the first 300 km. This is the only way in which the existence of an asthenosphere reflects itself in the rigidity of the earth, and this may not be related to its weakness but to some other property, such as the nature of compressibility or of changing chemical composition, or partly in the lack of detailed knowledge in the nature of the data.

Earthquake waves, like the tides, measure elasticity rather than strength. The vibrations which penetrate 200–300 km., and more, downward in the earth are already greatly reduced in amplitude and therefore in the strains which they bring on the earth. What the maximum strains may be is unknown, but reasonable assumptions as to amplitude show that within the asthenosphere the order of magnitude of the strains would be of the nature

[1] "On the Constitution of the Interior of the Earth as Revealed by Earthquakes," *Quar. Jour. Geol. Soc.*, LXII (1906), p. 470.

[2] P. 122.

of a thousandth part of that which granite at the surface of the earth can sustain. Furthermore, even if the stresses were greater and could be used as a measure of strength, this would apply to sudden stresses only and the results obtained from elastic vibrations could not be used safely as a means of determining the strength under long-enduring stresses. Thus the evidence from both tides and earthquakes is negative in regard to the existence of an asthenosphere. They show only that it is not fluid and that it is not markedly unlike the rest of the earth in its elastic properties.

HIGH, BUT VARIABLE, ELASTIC LIMIT WITHIN THE UPPER LITHOSPHERE

The experiments by F. D. Adams showed that under conditions of cubic compression rocks became far stronger than when subjected to compression, as at the surface of the earth, in one direction only. When a cylinder of Westerly granite was incased in a steel jacket and then subjected to heavy pressure upon its ends, a small cavity within the specimen just began to break down under a stress-difference of between 160,000 and 200,000 pounds per square inch, about six to eight times the strength possessed by this rock under surface conditions. At a temperature of 550° C., a temperature calculated to exist at a depth of 11 miles below the earth's surface, small cavities remained open when submitted to considerably greater pressures than occur from the overlying load at this depth.[1]

Adams' experiments and King's calculations are most important and show without doubt that the more superficial parts of the earth, to a depth of ten to fifteen miles at least, are far stronger than had been supposed; but they apply to the temperature and pressure gradients in places of geologic quiet, not to regions undergoing igneous intrusion and crustal deformation. Then the temperatures may become far higher and the crust surcharged with magmatic gases. Yet it is under these conditions especially, of geologic activity as contrasted to geologic quiet, that regional metamorphism and rock flowage proceeds. Still less does this experimental work prove a great strength of the crust at depths of more

[1] Louis Vessot King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Jour. Geol.*, XX (1912), 136, 137.

than a hundred kilometers, for there the temperatures are presumably above those which under the conditions of freedom from pressure at the surface of the earth produce dry fusion. Occluded gases, furthermore, are held beyond possibility of escape.

The strength of the crust is dependent consequently upon fourfold conditions—the nature of the material, the cubic compression, the relation of temperature to the point of fusion, and the rapidity of the application of the stress. These factors are all variable with time and place. How variable will be seen upon further consideration in the following paragraphs.

The influence of the nature of the material is seen when it is noted that granite is only about one-half as rigid as the basic rocks, although it is not less strong. Consequently, regional stress coming upon a complex of two such rocks will elastically deform the granite more readily, a greater stress will be thrown upon the basic rocks, and since their elastic limit is not correspondingly higher they should begin to yield by flow or fracture before the more pliant rocks had reached their limit. The general conclusion is that a movement of compression in the earth's crust must necessarily give rise to unequal strains and concentration of stress, as well from variations in chemical composition as from variations in structure. The local stress may rise far higher than the general regional stress.

As to the second factor, during the progress of normal faulting the horizontal compressive stress in the crust is less than the vertical stress due to weight. During the progress of folding and mashing, on the contrary, the horizontal stresses become far higher. But the least of the three principal stresses determines the amount of cubic compression; the difference between the greatest and least stresses determines, on the contrary, the amount and direction of the strain upon the rigidity of the rock. Thus it is seen that both the cubic compression and the stress-difference vary with the amount and kind of forces.

It is temperature, however, which is probably the most variable of these factors. Igneous activity brings the temperatures of the greater depths comparatively near to the surface and must produce

widespread weakening of the crust, both through the physico-chemical effects of the exalted temperatures and the structural effects of the intruded viscous fluids.

The rapidity of the application of stress is a variable in itself and furthermore has variable effects, but would seem, however, to be the least important of these several factors. The movements of horizontal compression and vertical warping are slow and give time for recrystallization in the deeper crust. In this way they meet a lesser resistance than would rapid stresses. Where the temperatures are close to those of fusion it would seem in fact that rock flowage by recrystallization, developing the gneissoid structure, should demand markedly less shearing stress than the process of granulation. The gnarled and twisted rocks of the Archean speak of the presence beneath them of molten magmas rather than of an enormous degree of compressive forces upon them. But ready yielding by recrystallization in one place would permit the concentration of mashing stresses upon other localities and raise the strain to that intensity needed for granulation. An enormous depth of cover, such as Adams' experiments have been thought to show, is not suggested by the geologic evidence, nor apparently is it demanded by a completer theory.

In fault movements and in dike or sheet intrusion accompanied by the expansion of gases are two sources of rapid application of forces. It is probable, however, that their deformative action is confined to the outer ten miles of the crust, and their consideration need not detain us in the evaluation of those factors of strength which concern the crust as a whole.

Summing up the conclusions from these various lines of evidence, physical and geological, it is seen that they suggest a rapid increase of strength with depth, then the gradual passage into a deep zone of lowered strength. The limits and values, however, are variable with time and place. Such a distribution of strength as is indicated by these independent lines is in accord with the interpretation of the geodetic evidence showing the existence of crustal competence to support heavy loads over certain limits of area, coexisting with flotational equilibrium over much broader regions.

MODES OF LITHOSPHERIC YIELDING AND THEIR RELATION TO STRENGTH

The relationship of strength to depth which has been derived in this study and which was expressed in the curve of strength at the end of Part VII is to be connected with the physical qualities discussed in this part. Here it is seen that it is a curve of elastic limit. When that limit is exceeded, permanent deformation must take place; by one means at the surface, by another within the body of the lithosphere, by still another at its base.

At the surface the typical mode of yielding is by jointing and faulting, in stratified beds by folding also. The movements in this zone of fracture and in the transitional zone of combined fracture and flow may be regarded as merely the responses in a thin, brittle, and relatively weak outer layer to deformative movements progressing in the great thickness of the lithosphere below. But the rocks of deeper origin which have been exposed at the surface by profound erosion show that they have yielded in another fashion. Their foliated structures and crystalline textures testify to yielding by massive flowage. Fracturing appears to have been absent, except in so far as it was produced by intrusions from below, giving rise to complexes of dikes and sheets. These visible exposures suggest that at still greater depths, notwithstanding the great strength of that zone, open fracture planes disappear and rock flowage both by granulation and by recrystallization is still more distinctive. This appears then to be the mode of yielding of the great body of the lithosphere.

Recently Becker has suggested that fracturing may enter into the problem of isostasy in the following way: The demonstrated capacity of small cavities to remain open under great pressures may permit fissuring and jointing to extend deeper into the crust than had been previously thought possible. To the degree to which fractures and porosities do exist they must decrease the specific gravity of rocks. If shattering pervaded the rocks of one region and not another, even though the rocks were exactly alike in composition, the densities would become different. To give isostatic equilibrium the region of shattered rocks would have to stand higher than the other. This would be the initial effect as

a result of the decrease in density, even if the zone of compensation rested on an unyielding base.[1] The logical correctness of this argument is not to be questioned, but rather the degree of its application. The following arguments suggest that shattering or porosity are, however, very subordinate rather than determining factors in the isostatic problem.

Such a theory does not account readily for the movements needed to maintain isostasy because of erosion and sedimentation. These surface changes of mass suggest a restoration of mass by lateral undertow. Furthermore, the appeal to nature shows that the rocks, once deep-seated, which have become revealed at the surface by erosion, are almost without pore space. The average porosity according to Fuller is 0.2 per cent, but the mean differences in densities between ocean and continent which must be accounted for under the hypothesis of uniform compensation to a depth of 122 km. amount to about 4 per cent.

Joints are observed to decrease with depth, becoming tighter and more distantly spaced, and the indications given by the lack of general circulation of ground-water through crystalline rocks, except within joint spaces near the surface, are that at greater depth the joint spaces are negligible.

In the great compressive movements the whole thickness of the crust must yield, but even this cannot be conceived as producing porosity by granulation sufficient to notably modify the density. A large part of the deformation in the deeper crust must be by a process of recrystallization. Assume, however, that granulation is the dominant process. Observation of granulated rocks shows a reduction in size of the crystals, but these broken fragments fit against each other perfectly and without great internal distortion of crystals. In granulated rocks from the zone of flow there is therefore always some amount of recrystallization, sufficient to eliminate that porosity connected with minute shattering and movement of the broken particles. The explanation appears to be as follows: The minute shattering of the minerals tends to give a high pore space, but with a high pore space the amount of contact

[1] G. T. Becker, "Isostasy and Radioactivity," *Science*, XLI (1915), 157–60; "On the Earth Considered as a Heat Engine," *Proc. Nat. Acad. Sci.*, I (1915), 81–86.

between grains becomes proportionately less. For the prevention of ready recrystallization and the maintenance of this pore space the granulated rock, according to present theory, must be conceived of as dry and the grains accordingly unsupported except at the points of contact. The shear strains within each grain become very great in proportion to the diminution of contact, and increase in proportion to the regional pressure. If the points of contact, for example, cover only one-fourth of the surface, the compression on those points would be four times as great per unit of surface as if there were continuous contact between grains. On the intervening parts of the surface there would be no pressure. Internal shears would result in this way from the hydrostatic pressure of dry rock due to depth and are not dependent upon a pressure-difference in the rock as a whole. The internal strains would tend to produce molecular changes of state as in the plastic flow of metals. There would be melting to relieve the strain, and refreezing by which the molecules would build out the crystals into the pore spaces. By this means recrystallization can go on without the aid of crystallizers, though presumably with more difficulty, and the comminuted crystals come to fit compactly as they are observed to do. This elimination of porosity presumably goes on approximately with the process of granulation, though it may lag somewhat. It would go forward more effectively with depth, irrespective of temperature, since there would be the greater static load upon the rock and the greater differential pressures within the mineral particles. It might be expected that such reduction of pore space would go forward to a limited extent only, leaving a residual porosity. Observation, however, shows that the pore space has been almost completely eliminated. Furthermore, the rocks now exposed at the surface acquired their absence of pore space at depths of only a few miles from the surface. At depths measured in tens of miles there seems then no expectation that density would be notably decreased because of a development of porosity.

To sum up the modes of yielding within the lithosphere: at the surface is seen to exist a thin outer crust intimately cracked on the outside by closely spaced parallel joint systems. Local

extreme deformation is by faults and folds. With increasing depth and strength the joints become less abundant and faults pass into flexures. The passage of fractures into flexures implies the beginnings of massive flow. Where magmatic heat or emanations are not present the mode of mashing is presumably more especially by granulation. With still greater depth the yielding becomes more uniformly distributed throughout the rock mass. Both because of this pervasiveness of mashing and the great strength of this zone, deformation here requires the most force and absorbs the most energy of any part of the lithosphere. At greater depths the rock is more compressed, and is still more rigid than above, but the temperature here approaches fusion; recrystallization readily takes place, the strain which can be elastically carried is in consequence low, and the lithosphere passes gradually into the asthenosphere. Where, however, magmas rise through the crust they carry with them the environment of the asthenosphere; the lithosphere becomes locally abnormally heated and saturated with magmatic emanations. Recrystallization goes forward readily and the zone of weakness penetrates upward even to the zone of fracture. Thus in the injected and crystallized roofs of ancient batholiths, laid bare by profound erosion, we may perceive the nearest approach to dynamic conditions which prevail in depths forever hidden.